SPLITS: Split Input-to-State Mapping for Effective Firmware Fuzzing

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Abstract. Ability to test firmware on embedded devices is critical to discovering vulnerabilities prior to their adversarial exploitation. Stateof-the-art automated testing methods rehost firmware in emulators and attempt to facilitate inputs from a diversity of methods (interrupt driven, status polling) and a plethora of devices (such as modems and GPS units). Despite recent progress to tackle peripheral input generation challenges in rehosting, a firmware's expectation of multi-byte magic values supplied from peripheral inputs for string operations still pose a significant roadblock. We solve the impediment posed by multi-byte magic strings in monolithic firmware. We propose *feedback mechanisms* for input-to-state mapping and retaining seeds for targeted replacement mutations with an efficient method to solve multi-byte comparisons. The feedback allows an efficient search over a combinatorial solution-space. We evaluate our prototype implementation, SPLITS, with a diverse set of 21 real-world monolithic firmware binaries used in prior works, and 3new binaries from popular open source projects. SPLITS automatically solves 497% more multi-byte magic strings guarding further execution to uncover new code and bugs compared to state-of-the-art. In 11 of the 12 real-world firmware binaries with string comparisons, including those extensively analyzed by prior works, SPLITS outperformed, statistically significantly. We observed up to 161% increase in blocks covered and discovered 6 new bugs that remained guarded by string comparisons. Significantly, deep and difficult to reproduce bugs guarded by comparisons, identified in prior work, were found consistently. To facilitate future research in the field, we release SPLITS, the new firmware data sets, and bug analysis at https://github.com/SplITS-Fuzzer.

Keywords: Fuzzing · Monolithic Firmware · Microcontroller

1 Introduction

Embedded device proliferation is creating new targets and opportunities for adversaries. Microcontrollers running firmware are becoming integral components



Fig. 1: Example of peripherals in a microcontroller's memory address space. Each peripheral contains multiple memory mapped registers within the peripheral's Memory Mapped Input/Output (MMIO) region a firmware can interact with.

of safety and security critical systems. In general, embedded devices take input from a diverse set of inputs and provide output in a unique manner, far different from those typically found on desktop computers. Integrated peripheral devices, such as timers or serial ports, manage communications with the user, often without any supervisory control from an operating system—*importantly*, the lack of supervisory control reduces the ability to detect faults and abort [25]. But, security is a crucial enabler for connected devices, making scalable and automated methods to identify software bugs and vulnerabilities prior to public release a research and societal imperative.

Fuzz testing, or fuzzing, is a de-facto industry standard for software testing and can play a crucial role in developing secure connected devices through scalable and automated testing of firmware. In fuzzing, inputs are automatically generated and run to uncover unusual program behavior [16]. But, the unique characteristics of embedded devices and their firmware present challenges for adopting fuzzing tools [25]. Fuzzing firmware based on their execution on physical devices [28,32,24,10,18] is hampered by dependence on execution on low performance embedded processors limiting fuzzing performance. To improve fuzzing throughput, the firmware can be rehosted [13] within an emulated environment on a high performance processor. While progress is made towards re-hosting and fuzzing Unix-based firmware [5,33,20,29,34], fuzzing monolithic embedded firmware presents a unique set of challenges [25,14,12,35,27,7,9,21]. A problem for rehosting for fuzzing arises from developing methods to automatically provide peripheral inputs to the multitude of memory mapped interfaces a firmware may access on these devices as illustrated in Fig. 1. In recent works [14,35,27,12,36], fuzzer generated test cases are fed to the framework rehosting the firmware, which uses this input stream to provide values to a set of peripheral registers, representing an interface used by a peripheral device (such as a modem or sensor). These approaches focus on ensuring data from peripherals can be successfully generated for the target.

A Firmware Fuzzing Roadblock. Existing methods to automatically manage peripheral inputs do not consider the problem posed by multi-byte magic values expected in peripheral inputs by firmware binaries. We observe software used to communicate with external devices often depends on magic bytes. For example, external devices such as modems or GPS modules follow text based communications, and communicate these messages to the firmware using interfaces managed by on-chip peripherals. Reaching key code sections accessing these external peripherals, as illustrated in Listing 1, requires the delivery of magic bytes expected by the binary, via peripheral accesses.

The problems posed by magic-values are recognized as a difficult hurdle for fuzzers to overcome in general. For non-firmware binaries, techniques in [2,17,8,1] are designed specifically to overcome these hurdles. The state-of-the-art technique for the problem in non-firmware binaries relies on *input-to-state mapping*, where a sequence of bytes from the fuzzer generated input is mapped to a program state variable such as the **input_buffer** in our example and are subsequently subjected to a surgical replacement by the magic values. Unfortunately, it cannot be simply employed for firmware.

Solving strings with input-to-state mapping techniques poses a unique challenge in firmware fuzzing due to the *unusual* and *diverse* input methods. While desktop applications read strings from a source, such as a file, as a contiguous block, embedded firmware processes *each* input byte from a peripheral, one at a time, each requiring multiple registers within the peripheral to be read. Additionally, *many peripherals are active simultaneously*, each with multiple memory mapped registers that influence firmware execution, as shown in Figure 1. Between each byte of data read by a given peripheral, numerous other peripheral registers are often accessed, causing the data bytes within the string sourced from the fuzzer generated input to be spread across a region. Consequently, the fuzz inputs mapping to the expected magic bytes are *unpredictably interspersed* throughout a large fuzz input. This prevents existing input-to-state mapping methods from identifying and solving string comparisons.

To address this gap, we consider a solution to the problem to advance recent progress made in monolithic firmware fuzzing to discover new software bugs previously guarded by magic-value roadblocks.

Our Approach. We propose new instrumentation and feedback to provide an effective method for input-to-state mapping and an optimized input replacement strategy to solve multi-byte string comparisons for fuzzing monolithic firmware.

The feedback derived allows an *efficient* search over the resulting *combina*torial solution-space by sequentially identifying the bytes in fuzz inputs corre-

1 2	<pre>char* input_buffer = NULL; while(true)</pre>	During fuzzing, <i>input_buffer</i> values must be read via correctly accessing the serial peripheral port
3	<pre>serial.println("AT");</pre>	1
4	input_buffer = serial.get	line();
5	if(strcmp(input_buffer,"0	<u>K") == 0</u>)
6	break;	

Listing 1: Simplified code snippet illustrating a wait for a peripheral device to respond OK to an AT command (extracted from **LiteOS IoT** binary). Failing to solve the string prevents execution of any deeper code, as the loop never exits.

sponding to those used in comparisons. Subsequently, we attempt to simultaneously replace all bytes to ensure the multi-byte comparison is solved. Further, we exploit the nature of string representations to craft new instrumentation providing further feedback to the fuzzer to retain seeds for targeted replacement mutations. Together, these techniques create a robust method to overcome multi-byte magic strings by providing a faster exploration of the combinatorial search space of potential solutions for feedback driven fuzzing frameworks that *simultaneously* provide input to many memory mapped peripherals.

Our Contributions. We make the following contributions through this study:

- We propose an effective method to overcome hurdles posed by multi-byte string comparisons common in monolithic firmware.
- To demonstrate the effectiveness of our techniques, we describe and build a prototype implementation, SPLITS, an effective method to consistently solve hard fuzzing problems dealing with multi-byte string comparisons without dependence on source code or debugging symbols for its implementation.
- In a series of extensive experiments with 24 real-world binaries, we demonstrate the method we propose is effective in significantly extending reachable code (up to 161% increase in blocks covered with SPLITS automatically solving 497% more multi-byte magic values) and discovering 6 previously unknown bugs (1 with a recent CVE assignment) guarded by string comparisons, compared to prior work; especially on binaries extensively analyzed by prior work. We responsibly disclose vulnerabilities to the affected groups.

To facilitate future research in the field, we will release SPLITS, the firmware data sets, and bug analysis at https://github.com/SplITS-Fuzzer. We begin with a technical primer on monolithic firmware to help understand the unique aspects that present a challenge for fuzz testing monolithic firmware.

2 Technical Primer

Monolithic Embedded Systems. Unlike Unix-based firmware, a single monolithic program controls all aspects of a device's operation. The application code, system libraries and hardware abstractions are combined into a single binary sharing the same memory space. The firmware manages all functions and interacts with peripherals such as buttons or GPS units through Memory Mapped Input/Output (MMIO), hardware interrupts and Direct Memory Access (DMA).

MMIO. MMIO is a predefined segment of memory reserved for communicating directly with peripherals through reads and writes to the peripheral's registers. As shown in Figure 1, each peripheral has a set of data, control and status registers. **Data registers** contain the data to be read or written. **Control registers** store the parameters for the peripheral's operation, such as speed or operating mode. **Status registers** describe the current state of the peripheral, indicating the presence of new data, or any errors. For **Status** and **Control** registers, it

is common for many individual bits within a register to have distinct purposes and many components of the peripheral's state are condensed to a few registers.

While peripherals such as timers and Analog to Digital Converters (ADCs) are embedded on-chip, not all peripherals are integrated directly into a microcontroller. Instead the microcontroller can be connected to other hardware components such as wireless modems. These external devices communicate with the microcontroller to provide data not observable with only the built in on-chip peripherals. To facilitate this communication, integrated peripherals are implemented to control data buses. Some examples are the Serial Peripheral Interface (SPI), Inter-Integrated Circuit (I2C) and Universal Asynchronous Receiver Transmitter (UART). In each case, the firmware accesses external peripherals through an MMIO interface exposed by these integrated peripherals, to read and write data to the bus.

Hardware Interrupts. Peripherals also interact with firmware by generating interrupt signals, indicating an event has occurred. The CPU immediately jumps to an interrupt handler associated with the given signal, reads the peripheral status, and performs any necessary operations to handle this signal. Depending on the current status, handling the signal may involve reading new data, writing data to the peripheral, or discarding data containing errors. Afterward, the CPU returns to its prior location to continue its previous task.

3 The Input-To-Sate Mapping Problem

The use of multi-byte magic values in the form of strings occurs regularly on embedded devices. These devices can use strings to take instructions on how they should operate, such as the use of GCode commands on a 3D Printer. Alternatively, firmware can communicate with external peripherals using strings. We observe this to be the case for AT commands used to communicate with modems, similar to the initialization example in Listing 1. Here, if the device does not respond with the string OK, the while loop will never exit, and the firmware will not proceed further. State-of-the-art methods use Input-To-State (ITS) mapping to overcome such hurdles. The goal is to solve this comparison by observing the value in *input_buffer* and locating it within the fuzzer generated test case, and replacing it with the ideal value OK.

Existing input-to-state mapping techniques are effective for binaries where fuzzer generated data is loaded as a contiguous block for processing. But, *firmware typically loads fuzzer generated input data over peripherals over a period of time*, byte by byte with frequent switching between tasks for different peripherals, and uses multiple register accesses for each byte of input. This behavior **prevents the** observed data from being contiguous in the fuzz input. Figure 2 shows an example of firmware using fuzzer generated input, prior to reaching the string comparison described in Listing 1, and a similar example for a desktop application. While the desktop application code loads the bytes 0x61, 0x36, corresponding to the ASCII string a6, the firmware example loads ac from a UART serial port through multiple MMIO register reads, intermitted by other



Fig. 2: Excerpt of a fuzzer generated input consumed for a sequence of register reads for multiple active peripherals. The UART serial port loads the bytes **a** (0x61) at time t2 and **c** (0x63) at time t9. The values read from the serial port are used to form the string **ac**. Although, adjacent in *input_buffer*, **a** and **c** are separated in the fuzzer generated input due to the unpredictable number of other peripheral register reads from t3 to t8. In contrast, a desktop application loads the data in a block with the bytes adjacent in the input and *input_buffer*.

peripheral accesses. While the string **a6** does appear in the fuzzer generated input, the string **ac** does not. Consequently, mapping the *observed* value back to the fuzzer generated input is not trivial. This prevents existing input-to-state mapping methods from identifying and solving string comparisons.

To address this gap, we develop an input-to-state mapping technique for monolithic firmware. Through our efforts, we aim to advance recent progress made in monolithic firmware fuzzing to discover new software bugs previously guarded by magic-value roadblocks.

4 Split Input-to-State Mapping

Consider Fig. 2. A naive approach to solve the non-contiguous string is to *at*tempt all possible combinations of replacements for each character in the observed string with the corresponding character in the *ideal string*. While the approach may be possible for the example in Listing 1, where the string comparison only depends on solving two characters, this solution does not scale, instead creating a combinatorial problem. The number of executions required to test all possible combinations depends on two factors: the length of the string and the number of candidate bytes for replacement in the fuzzer generated input. Notably, we observe strings up to 18 characters in length, and fuzzer generated inputs with thousands of bytes. These large inputs and strings lead to creating a large search space infeasible to test effectively, as shown in the following examples.

Example 1: Long Strings. Consider the string, rpl-refresh-routes observed in the Contiki-NG binary. When three candidates for each of the 18 characters are considered, the number of possible combinations rapidly explodes. This string would require more than three hundred million combinations be tested.

Example 2: Many Candidate Bytes. Consider the string poweron observed in the Console binary. When 16 candidates for each of the seven characters are considered, more than two hundred million combinations would be tested.

To illustrate how the naive approach is influenced by the inclusion of longer strings and more candidates for each character, we refer to the naive search (1) in Figure 3. This example uses a four character string, each with four occurrences in the fuzzer generated input that are candidates for replacement. This results in 256 possible combinations. Each additional character has a multiplicative impact on the number of combinations to test. The number of occurrences of this additional character in the fuzz input defines the scale of this multiplicative impact. While certain constraints can be implied, such as those discussed in Section 4.2, to remove some combinations, a naive approach is impractical and highly inefficient, as it does not prevent the extreme growth in search space resulting from this method.

4.1 Feedback Guided Search

Rather than considering the possible combinations of replacements, we consider a more scalable approach guided by *whether a given byte influences the string comparison*.

Comparison Feedback. To successfully replace memory comparisons based on non-contiguous accesses, without introducing an explosion in candidate replacements, we attempt to solve each byte individually. We propose monitoring the data present in the *observed* and *ideal* value buffers, and *use the content of the buffers as feedback mechanism*. If the current byte has successfully been updated within the *observed buffer*, we only consider combinations that include this byte. If this value remains unchanged, or the comparison is not reached, we proceed to the next candidate location within the input and no longer consider any replacements that include this byte. This is done until all bytes in the *observed buffer* match the byte at the corresponding index in the *ideal buffer*, or an *observed buffer* byte could not be located in the input.

Figure 3 (2) shows the feedback guided search in an example, progressively locating the 'A', 'B', 'C' and 'D' characters within an input that loads ABCD into a buffer. Bytes that have been confirmed to be a part of the observed buffer are highlighted in green. Tested bytes that do **not** correspond to a byte in the *observed buffer* are shown in red; such as the first 'A' tested once before exclusion. Additionally, the fourth 'A' character is quickly discarded from the search space (shown in gray), as a valid replacement for this character in the *observed buffer* has already been identified. When compared to the naive search, the number of

Code Example		strcmp(input_buffer , "Test") "ABCD"					
Fuzzer Generated Input Ch	aracters	ADABCBDBCACCDBDA					
1 Naive Search ADABCBDBCACCDBDA ADABCBDBCACCDBDA	2 Comparison Guided S A D A B C B D B A D A B C B D B A D A B C B D B A D A B C B D B A D A B C B D B A D A B C B D B A D A B C B D B A D A B C B D B A D A B C B D B A D A B C B D B A D A B C B D B A D A B C B D B A D A B C B D B A D A B C B D B A D A B C B D B A D A B C B D B A D A B C B D B A D A B C B D B A D A B C B D B A D A B C B D B	Feedback Search C A C C D B D A C A C C D B D A	 3 Optimized Comparison Feedback Guided Search (Algorithm 1) A D A B C B D B C A C C D B D A A D A B C B D B C A C C D B D A A D A B C B D B C A C C D B D A A D A B C B D B C A C C D B D A A D A B C B D B C A C C D B D A A D A B C B D B C A C C D B D A A D A B C B D B C A C C D B D A A D A B C B D B C A C C D B D A A D A B C B D B C A C C D B D A A D A B C B D B C A C C D B D A A D A B C B D B C A C C D B D A 				

Fig. 3: Example of naive vs. feedback guided search of the string "ABCD" within a fuzzer generated input consisting of four As, Bs, Cs and Ds. In (1), the four occurrences of the character 'D', creates four additional cases to test **for each combination** of the string "ABC", causing the search space to be four times larger than searching for the string "ABC" within the input. The same addition for the feedback guided searches (2) & (3) only adds, at most, four more tests.

firmware executions required to solve the string comparison is greatly reduced. As each candidate byte in the fuzzer generated input can only be considered for replacement once, this method only has linear complexity with regard to the string length, and number of candidates for each character.

Length Feedback. Comparison feedback alone is not adequate for an effective search and replacement strategy. Strings must be the same length to be equal. In cases where the observed string—values generated by the fuzzer for a peripheral—is shorter than the *ideal string*, we do not have any knowledge of which bytes need to be mutated to extend the observed string to the required length. But, during fuzzing, we can expect many executions to contain different strings of varying lengths. However, due to the coverage metrics used by greybox fuzzers, if the inputs only reach the same code, they are rarely saved for further processing. Thus, we rarely recall seeds with long enough strings to attempt replacement of the observed string. To address this issue, we include additional coverage instrumentation. We exploit the null byte in string formats to determine their length. By searching for null terminators in the observed and *ideal* buffers, we can determine the length of the *observed string* and *ideal* string. When a string comparison is identified, we ascertain the string lengths, and count previously unseen observed string lengths similar to the length of the ideal string as interesting. This ensures we save inputs that load sufficient data into the observed string buffer for successful replacement with the *ideal string*.

4.2 Search Optimizations

To further minimize the effort required to discover useful inputs, we consider several *intuitive* but *effective* optimizations to reduce the number of combinations considered and improve applicability. These optimizations are combined with the comparison feedback described in Section 4.1 to develop Algorithm 1.

Constrained Mutable Regions. We constrain the sections of the input considered valid for mutation. We expect any data that has not been read prior to the comparison, cannot influence the result of the comparison. Consequently, we do not attempt to mutate these bytes. This reduces the maximum number of iterations of the inner loop in Algorithm 1.

Implied Sequential Access. In the context of firmware, we can assume that data, whilst not adjacent, is read in sequence (i.e. read of the second byte in the string occurs a period after the first) due to the stream-like nature of the input. Consequently, for all *observed buffer* bytes after the first, we exclude any input bytes that have not been read since the previously solved byte in the *observed buffer* was accessed. This reduces the range of j in the inner loop of Algorithm 1.

Algorithm 1: Feedback Guided Search & Replacement Algorithm for solv-
ing a string comparison. A comparison identifiable by <i>cmp_id</i> , reached when
executing the firmware with <i>input</i> , requires the <i>observed_string</i> to match
the <i>ideal_string</i> . <i>GetReadBytes</i> returns the number of input bytes read at
the time of comparison, and <i>InsertDelimiter</i> replaces a byte in a string with
common tokenization delimiters.

_		
	input: input, ideal_string, observed_string, cmp_id	
1	$original_input \leftarrow input$	
2	$last_index \leftarrow 0$	
	/* For each byte value to be replaced	*/
3	for $i = 0$ to observed_string.length do	
4	for $j = last_index$ to GetReadBytes (cmd_id) do	
	/* If this input byte is a candidate for replacement	*/
5	if $observed_string_i = input_j$ then	
6	$input_j \leftarrow ideal_string_i$	
7	Execute(input)	
8	$new_observed \leftarrow \texttt{GetObserved}(cmp_id)$	
9	if $new_observed.exists$ and $new_observed_i = ideal_string_i$ then	
10	$last_index \leftarrow j+1$	
11	break /* Solved. Move to next byte.	*/
12	else	
13	$input_j \leftarrow original_input_j /*$ Not solved. Restore byte	*/
14	if $j = \text{GetReadBytes}(cmp_id)$ then	
15	return /* Unable to map byte	*/
16	if $i >= ideal_string.length$ then	
17	InsertDelimiter(<i>observed_string</i> , <i>i</i>) /* Shorten observed string	*/
18	return	



Fig. 4: Overview of SPLITS design. The Instrumentation and Feedback component provides string comparison and length feedback. Length feedback is implemented by setting bits within the existing fuzzer coverage bitmap (Section 4.1). The compared strings and information on which bytes of the mutated input have been read are provided to the SPLITS Search & Replace module, where the comparison is solved, guided by incremental feedback (Algorithm 1).

String Contractions. For strings to be equivalent, both strings must be the same length. While we can not extend the *observed string*, we can attempt to shorten it. When the *observed string* is longer than the ideal string, we identify the byte corresponding to the next character in the *observed string* and attempt replacement of this byte with a set of common token delimiters such as space and newline, contracting the string to the correct size.

In Figure 3, we illustrate the impact of using the optimizations in block (3). The optimizations reduce the number of executions required to identify the bytes in the comparison compared to the search in (2) guided solely by feedback.

5 Implementation

We provide an overview of a realization of our techniques for a monolithic firmware fuzzer in Figure 4. To test the efficacy of our approach, we implemented our method with FUZZWARE [27]. We also apply the FERMCov technique described in EMBER-IO [12] as it can increase the effectiveness of the framework. In particular, FUZZWARE's emulator was modified to detect potential string comparison functions, and report the location and buffer contents for each of these function calls to the fuzzer, AFL++ [16]. We implement our string replacement on top of AFL++'s existing *cmplog* interface. AFL++ was configured to use random bytes for colorization, and only consider string comparisons for input-to-state solving.

Given that embedded system fuzzing frameworks such as FUZZWARE use the AFL++ generated input as a stream, where each byte is only read once and in order, we use the cursor location within the stream to determine which data has been read at a given time. All bytes at a lower index than the current cursor have been read, and equal or higher indexes are unread. We pass the cursor index at the time of comparison from the SPLITS feedback inside the emulator back to

AFL++ as an extension to the *cmplog* interface. This knowledge of unread bytes is used as described in Section 4.2. The index of the previously solved byte is determined internal to AFL++ during SPLITS' replacements.

Similar to the original REDQUEEN [2] implementation, we detect comparison functions by hooking instructions used to call functions, and analyzing the parameters. In the case of ARM, we hook the branch linked (BL) instruction, and read the R0 and R1 registers, corresponding to the first two function parameters. A function is considered a potential memory comparison function when the first two parameters are valid memory pointers, where one points to ROM (assumed to be the *ideal string*), and the other to RAM (assumed to be the *observed string*). Our implementation does not require modifications to the firmware's source code or binaries, nor does it depend on debug symbols being present.

To handle nested substring checks within the same string, SPLITS is configured to attempt replacement at both the start and end of a string buffer, provided the current *observed string* is longer than the *ideal string*.

6 Evaluation

To determine SPLITS' effectiveness at solving non-contiguous string comparisons, we evaluate it on a set of monolithic real-world firmware. We analyzed the binaries used in evaluations from existing firmware fuzzing frameworks P^2IM [14], µEmu [35], FUZZWARE [27] and EMBER-IO [12] that emulate memory mapped IO. From the 21 real-world firmware used in the coverage comparisons, nine contain functionality guarded by string comparison functions such as *strcmp*, *strncmp* and *strstr*. We additionally included three *new* targets containing string comparisons. Each binary is fuzzed for 24 hours in five trials. To ease the analysis, we considered the binaries in the following groupings:

- Magic-String-Binaries. We examined a set of 24 real-world binaries and observed magic values used in string comparisons in 12 of the binaries. We employed this set for our extensive evaluations.
- Other-Binaries. The remaining 12 real-world binaries that did not make use of any string comparisons to guard code execution.

We conduct evaluations with and without SPLITS. Here, the fuzzer without our techniques is the state-of-the-art FUZZWARE improved with FERM-Cov (denoted simply as FUZZWARE) while the SPLITS denoted implementation is FUZZWARE improved with FERMCov along with our proposed techniques. FUZZWARE [27] has previously shown higher code coverage and bug finding performance when compared to prior works such as P^2IM [14] and μEmu [35]. ICICLE with CompCov is included for a point of comparison as CompCov instrumentation could solve some string comparisons. We also included the recent state-of-the art monolithic firmware fuzzing framework, EMBER-IO. Tests were performed using an AMD Threadripper 3990X. We used the gathered coverage information and crashing inputs to answer the following questions:

Table 1: The number of reached string comparisons guarding code solved across five 24 hour trials in the *Magic-String-Binaries. Total* represents the number of unique comparisons solved at least once across all of the trials. SPLITS outperforms state-of-the-art fuzzing techniques and is demonstrably highly effective and yield *consistent* performance across repeated runs.

		Fuzz	ZWARE	;	ICI	CLE (Comp	oCov)	Splits			
Firmware	Min	Med	Max	Total	Min	Med	Max	Total	Min	Med	Max	Total
3D Printer	0	0	0	0	0	0	1	1	4	4	4	4
Console	1	1	2	2	2	3	6	9	15	15	15	15
GPS Tracker	0	0	0	0	0	0	0	0	4	4	4	4
LiteOS IoT	0	0	1	1	0	0	1	1	1	1	1	1
RF Door Lock	0	0	1	1	0	1	1	1	1	1	1	1
Steering Control	0	0	0	0	0	0	0	0	2	2	2	2
uTasker MODBUS	0	0	0	0	0	0	0	0	44	45	45	45
uTasker USB	0	0	0	0	0	0	0	0	31	33	34	34
Zephyr SocketCan	2	26	30	30	29	32	33	40	52	55	60	65
ChibiOS RTC	0	0	1	2	0	0	2	2	14	14	14	14
Contiki-NG Shell	0	0	0	0	0	0	0	0	14	14	14	14
RiotOS TWR	0	0	0	0	0	0	0	0	13	13	16	16

- 1. How successful is SPLITS at solving string comparisons? (Section 6.1)
- 2. Does the solving of string comparisons provide a significant increase in reachable code? (Section 6.2)
- 3. Does SPLITS impact fuzzing firmware with no comparisons? (Section 6.2)
- 4. How does SPLITS impact the discovery of firmware bugs? (Section 6.3)

6.1 Effectiveness at Solving Strings

Table 1 shows the ability of FUZZWARE, SPLITS and ICICLE with CompCov to solve multi-byte string comparisons that guard further code exploration. The results show using FUZZWARE alone struggled to solve the majority of the string comparisons. For those that were solved, the ability to solve a given string was rarely consistent across the five trials. ICICLE with CompCov was able to solve some strings unreachable by FUZZWARE in the 3D Printer, Console and Zephyr SocketCan binaries. In contrast, SPLITS was able to perform significantly better and more consistently; solving all of the same strings across all trials for eight of the twelve binaries tested (i.e. the *Min* and *Total* results were equal). In the remaining cases, the majority of strings were consistently solved, but a handful were not consistent as additional constraints prevented the fuzzer from reaching the string comparison. These constraints included the number of parameters given after a command, or other aspects of the system state that must be correctly set in conjunction with the provided string.

Performance Analysis. For a deeper understanding of the effectiveness of our approach, we evaluated the efficiency with which comparisons are solved by SPLITS compared to the state-of-the-art in **Appendix** A.1

6.2 Code Coverage Analysis

We analyze code coverage over the two categories of firmware we devised (*Magic-String-Binaries* and *Other-Binaries*) to understand the effectiveness of SPLITS and determine if the introduction of the techniques impacts fuzzing performance.



Fig. 5: *Magic-String-Binaries*. Comparison of coverage achieved by: FUZZWARE, SPLITS, EMBER-IO and ICICLE with CompCov for *Magic-String-Binaries*. Bands represent the range of coverage observed over five 24 hour trials.

The introduction of SPLITS has a large impact on code coverage for several of the firmware, shown in Figure 5 and **Appendix** A.2. Of the twelve Magic-String-Binaries, eleven had higher results deemed statistically significant when applying a Mann-Whitney U test at the 0.01 significance level. When compared to other frameworks, SPLITS saw an increase deemed statistically significant in 9 and 10 of the twelve binaries for EMBER-IO and ICICLE respectively.

Compared to the other tested firmware fuzzing frameworks, SPLITS saw more than a 50% increase in code coverage in both the uTasker MODBUS and the ChibiOS RTC binaries. We observed improvements upwards of 37% for the Console binary, 23% for the Contiki-NG Shell binary, and 17% for the RiotOS TWR binary in median blocks covered when compared to the other frameworks. The GPS Tracker and Zephyr SocketCan binaries each saw an increase in median code coverage between 5 and 10% compared to the next highest framework.

The string comparisons guarding initialization for the RF Door Lock and LiteOS IoT binaries are observable in the coverage results. FUZZWARE could

not consistently find a valid solution in 24 hours. This led to much higher minimum and median coverage results for SPLITS, an increase of more than 80% in each of these cases. Due to FUZZWARE and EMBER-IO both solving the string comparison in the RF Door Lock in a single trial, statistical significance could not be established. In contrast, ICICLE with CompCov allowed solving the RF Door Lock binary's string comparison in the majority of tests. Interestingly, EMBER-IO was able to consistently find an input passing the two character string comparison found in the LiteOS IoT binary.

Block coverage in the 3D Printer increases more than 100% when SPLITS is applied compared to FUZZWARE. Most of the commands given to the 3D Printer firmware are parsed byte by byte, rather than as a string. The string comparisons come from a handful of exceptions, such as the emergency stop command M112. The number of code blocks reachable from these special cases is too small to account for the change increase in coverage from enabling SPLITS. Further investigation reveals that solving a single command can provide a mutable case with the correct format. After the M112 emergency stop command was solved with SPLITS, mutation yielded discovery of the similar M111 and M113 commands. EMBER-IO was also able to uncover many of these commands.

Given the large difference in the number of solved strings between FUZ-ZWARE and SPLITS on the uTasker USB firmware, we consider the difference in the number of blocks reached comparatively small. Further investigation revealed that SPLITS and FUZZWARE explored different parts of the firmware. Of the 2266 unique blocks executed across all runs, 226 were only reached using FUZZWARE, while 437 blocks could only be reached when SPLITS was applied.

Code Coverage of Other-Binaries. SPLITS is intended to solve strings, the attempts to solve strings require firmware executions to both search for, and attempt to solve potential string comparisons. To determine whether the additional processing impacts fuzzing of firmware with no string comparisons, we tested the *Other-Binaries* and compare the coverage results to FUZZWARE without SPLITS applied. We defer the results to **Appendix** A.2. In summary, none of the tests revealed a statistically significant difference in coverage achieved; this suggests that fuzzing performance is not impacted by SPLITS.

6.3 Bug Discovery

While code coverage is a useful metric for comparing the performance of fuzzing frameworks, fuzzing aims to identify bugs. We deduplicated the reported crashes and investigated any crashes in these binaries identified with SPLITS that were not previously found and reported by FUZZWARE.

Analysis of Newly Discovered Bugs. After triaging the deduplicated crashes, we identified the following new firmware bugs, and verified they are not false positives. We responsibly disclosed any vulnerabilities to the appropriate vendor.

(1) **Zephyr SocketCan.** *CVE-2023-0779.* Within Zephyr's network component, we identified a command used to provide information about internal packet

buffers. The function takes a parameter in the form of an address pointer, directly from the user. This pointer is not validated beyond checking if it is null, allowing a user to point at any location in memory.

(2) Console. Within the Console binary, we identified an out-of-bounds read bug. Commands take input from the user regarding dates, without validation. Entering months greater than 12 causes data from outside an array to be read. We note this bug was concurrently discovered in ICICLE [7], when used with CompCov [16], which we replicated in one of our five trials.

(3) uTasker MODBUS & uTasker USB. The uTasker binaries previously tested in FUZZWARE [27] were compiled with the *MEMORY_DEBUGGER* enabled. This allows reading and writing arbitrary memory. While this is a valid method to crash the firmware, and ideally attempts to access unmapped memory would be restricted, we do not consider this a vulnerability, as these commands are expected to be disabled in release versions of firmware.

(4) Contiki-NG Shell. The Contiki-NG Shell binary does not always validate the number of parameters given to a shell command. Attempting to call a vulnerable command with fewer parameters causes the parameter pointer to be set to null. This null pointer is not checked prior to being dereferenced.

(5-6) GPS Tracker. We uncovered two new crashes, both null pointer dereferences caused by a lack of error checking. For the first bug, the code assumes a call to *strtok* will always return at least one token, and fails to consider the case where the input is an empty string. The second bug fails to consider a received string may not contain an expected value. Searching for the expected substring results in a null pointer being returned when it is not found, then dereferenced. This bug is identical in nature to a known bug in this firmware, and appears to be caused by copy-pasting the flawed code to other sections of the firmware.

Analysis of Existing Bugs Guarded by String Comparisons. Notably, the inclusion of SPLITS does not change the execution of a given fuzzer generated input. Other mutation stages such as *havoc* and *splice* employed by AFL++ can still produce inputs that trigger the crashes previously reported by FUZZWARE. We observe two bugs previously reported by FUZZWARE are guarded by string comparisons. The GPS Tracker contains a null pointer dereference when parsing AT commands. In our tests, none of the five FUZZWARE trials triggered this bug. The RF Door Lock contains a bug in the main loop, requiring the string comparison in initialization to be solved. This deeper bug was triggered in one of our five FUZZWARE trials, as the others were unable to proceed past initialization. SPLITS, was able to reproduce both bugs in **all** five trials.

7 Discussion

Comparison Functions. Predominantly, we observed standard C functions for comparing strings. But, in the two uTasker binaries, a custom function performs string comparisons, fnCheckInput. However, the custom function is detected as a string comparison function and appropriately solved. This suggests SPLITS can

be applicable outside of the standard C functions. Notably, the use of functions to perform comparisons is extremely common but it could be performed inline, preventing the string comparison from being detected and solved using SPLITS. However, we have not observed this problem in our testing.

Comparison Detections. We observed some cases of false positive detection of string comparison functions. One example is printing to a serial port. The static string to be printed is detected as an *ideal string*, while the pointer to the serial device is detected as an *observed buffer*. This has little significance. Because the only impact from these false positives is taking extra computation time but time loss is already minimized, as we do not expect to be able to map the input to many of the serial port's internal variables. If a byte cannot be mapped, further processing of this comparison is abandoned.

Applicability to Other Frameworks. While we have implemented SPLITS on top of FUZZWARE [27], it is also applicable to other monolithic embedded firmware fuzzing frameworks such as P²IM [14], μ Emu [35] and Ember-IO [12]. In the case of Ember-IO, there is an additional requirement that *peripheral input playback* was not the source of any of the bytes in the observed value buffer; as only fuzzer generated input bytes can be located using input-to-state mapping. We consider DMA out of the scope, and the application of SPLITS to works that handle DMA such as DICE [23] and SEmu [36] has not been considered.

8 Related Work

Embedded Firmware Fuzzing. In general, for Unix-based firmware, several approaches have been developed [5,33,20,29,34]. While acknowledging these efforts, in this study, we focus on fuzzing approaches for monolithic firmware.

Monolithic Embedded Firmware Fuzzing. To function on monolithic firmware, some works replace hardware interactions at a Hardware Abstraction Layer [21,9], assisted by manual effort. To automate this process, works such as P^2IM [14] and μEMU [35] use heuristic based models to classify individual registers and infer the behavior of each classification. Several works have explored the use of symbolic execution as a tool to assist in firmware testing [35,11,19,4,22]. SEMU [36] instead models the behavior of peripheral registers by processing the manufacturer's manuals. Approaches such as EMBER-IO [12] and FUZZWARE [27] fuzz all registers, and simplify the process by reducing the amount of mutation required.

Input-to-State Correspondence Methods. Early methods to assist multibyte comparisons such as LAF-INTEL [1] and CompCov [16] replace these comparisons with a series of easier to solve single byte comparisons. Alternate approaches used symbolic execution [3,30] or taint tracking [26,6,31,17] as a means to uncover paths with difficult to solve constraints. Eclipser [8], REDQUEEN [2] and WEIZZ [15] use input-to-state mapping for non-firmware binaries to inform replacement mutations. These desktop-focused approaches assume contiguity between program state and inputs when solving string comparisons.

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9 Conclusion

To allow firmware fuzzers to appropriately solve string comparisons found in many firmware, we developed SPLITS. When integrated with FUZZWARE [27] and AFL++ [16], our instrumentation and mutation techniques were effective in finding test cases suitable for string replacement, and efficiently performing the replacement to reach deeper code. Eleven of the 12 tested firmware containing string comparisons demonstrated statistically significant improvements in block coverage compared to the baseline FUZZWARE with 6 *new* bugs (with one recent CVE assignment) in firmware found through the inclusion of SPLITS.

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A Appendix

A.1 Detailed Performance Analysis

For a deeper analysis of the effectiveness of our approach, we selected three sets of firmware based on their use of strings to determine the efficiency with which comparisons are solved by SPLITS compared to the state-of-the-art fuzzers.

As shown in Table 2, SPLITS was able to quickly and consistently solve the error checks in the LiteOS IoT and RF Door Lock binaries. Neither FUZZWARE or ICICLE with CompCov could consistently solve these comparisons. For FUZ-ZWARE, only a single run for each binary was able to pass this comparison and reach the main loop. In our 3D Printer and Steering Control tests, using strings to receive data, SPLITS solved all of these comparisons. In cases where multiple, similar length, strings are compared in quick succession, SPLITS would solve each of these strings within seconds of each other. FUZZWARE did not solve any of these comparisons, while ICICLE with CompCov only solved a single string from this set. For the console binary, with SPLITS, all string comparisons were solved in every run, while FUZZWARE alone solved the shortest string, ps consistently, and the second shortest string rtc in a single run. ICICLE with CompCov solved more strings than FUZZWARE due to CompCov instrumentation, but still lacked consistency and the process took considerably longer than SPLITS.

Table 2: Time to solve a sample of string comparisons over five 24 hour fuzzing
campaigns. The fastest minimum, median and maximum values for each firmware
are shown in bold and gray regions show failures.

	Fu	ZZWAI	₹E	ICICLI	e (Comp	Cov)	SplITS			
Firmware	String	Min	Med	Max	Min	Med	Max	Min	Med	Max
LiteOS IoT	OK	2h13m	>24h	>24h	18h23m	>24h	>24h	19m	1h2m	1h32m
RF Door Lock	OK r n	1h1m	>24h	>24h	2h53m	20h28m	>24h	2m	4m	10m
3D Printer	M108	>24h	>24h	>24h	>24h	>24h	>24h	11m	23m	44m
3D Printer	M112	>24h	>24h	>24h	11h7m	>24h	>24h	11m	23m	44m
3D Printer	M410	>24h	>24h	>24h	>24h	>24h	>24h	11m	23m	44m
3D Printer	M110	>24h	>24h	>24h	>24h	>24h	>24h	46m	1h33m	1h59m
Steering Control	steer	>24h	>24h	>24h	>24h	>24h	>24h	6m	8m	13m
Steering Control	motor	>24h	>24h	>24h	>24h	>24h	>24h	6m	8m	13m
Console	ps	3m	41m	2h22m	2m	24m	1h25m	2m	3m	7m
Console	reboot	>24h	>24h	>24h	13h47m	>24h	>24h	2m	6m	7m
Console	help	>24h	>24h	>24h	3h40m	21h52m	>24h	2m	6m	6m
Console	saul	>24h	>24h	>24h	9h3m	>24h	>24h	2m	6m	$7\mathrm{m}$
Console	write	>24h	>24h	>24h	>24h	>24h	>24h	54m	1h25m	4h25m
Console	read	>24h	>24h	>24h	>24h	>24h	>24h	51m	1h4m	3h22m
Console	all	>24h	>24h	>24h	>24h	>24h	>24h	1h5m	1h14m	4h19m
Console	rtc	14h30m	>24h	>24h	4h58m	>24h	>24h	2m	3m	$7\mathrm{m}$
Console	poweron	>24h	>24h	>24h	9h25m	>24h	>24h	7m	1h26m	1h40m
Console	poweroff	>24h	>24h	>24h	9h38m	>24h	>24h	7m	1h26m	1h40m
Console	clearalarm	>24h	>24h	>24h	>24h	>24h	>24h	7m	1h26m	1h40m
Console	getalarm	>24h	>24h	>24h	18h40m	>24h	>24h	7m	1h26m	1h40m
Console	setalarm	>24h	>24h	>24h	20h37m	>24h	>24h	31m	1h48m	4h28m
Console	gettime	>24h	>24h	>24h	>24h	>24h	>24h	7m	1h25m	1h39m
Console	settime	>24h	>24h	>24h	>24h	>24h	>24h	31m	2h15m	3h17m

A.2 Code Coverage (Magic-String-Binaries and Other-Binaries)

Table 3 and Table 4 show the coverage achieved in the *Magic-String-Binaries* and *Other-Binaries* respectively.

Table 3: *Magic-String-Binaries*. Fuzzing minimum, median and maximum block coverage achieved with each fuzzing framework over five 24 hour fuzzing campaigns. P-Values indicating statistical significance are calculated using Mann Whitney U tests, conducted at a 0.01 significance level. The highest minimum, median and maximum values for each firmware are shown in **bold**.

	Fuzzware			Ember-IO			ICICLE (CompCov)			SplITS						
Firmware	Blocks in	Min	Med	Max	Min	Med	Max	Min	Med	Max	Min	Med	Max	p-val to	p-val to	p-val to
	Firmware	rmware Min Ned Max Min Ned Max Min Ned Max		in mod		Fuzzware	Ember-IO	ICICLE								
3D Printer	8045	1229	1289	1383	1575	3517	4059	1311	1445	2988	2695	3134	3614	< 0.01	0.465	0.016
Console	2251	803	805	844	804	843	856	808	830	1063	1157	1160	1161	< 0.01	< 0.01	< 0.01
GPS Tracker	4194	747	748	754	756	756	759	748	750	753	827	830	833	< 0.01	< 0.01	< 0.01
LiteOS IoT	2423	736	737	1346	1347	1348	1350	736	736	1313	1358	1366	1368	< 0.01	< 0.01	< 0.01
RF Door Lock	3320	781	782	2548	782	782	2662	780	1177	2380	2539	2553	2687	0.015	0.067	< 0.01
Steering Control	1835	609	613	620	638	644	648	610	613	615	643	648	652	< 0.01	0.169	< 0.01
uTasker MODBUS	3780	1244	1246	1280	1219	1252	1311	1246	1303	1303	2042	2052	2100	< 0.01	< 0.01	< 0.01
uTasker USB	3491	1734	1745	1775	1341	1351	1360	1520	1540	1862	1792	1815	1934	< 0.01	< 0.01	0.047
Zephyr SocketCan	5943	2689	2976	3029	2272	2468	2565	2733	2806	2809	3093	3126	3135	< 0.01	< 0.01	< 0.01
ChibiOS RTC	3013	559	578	593	554	558	565	554	567	575	1002	1005	1007	< 0.01	< 0.01	< 0.01
Contiki-NG Shell	4776	1593	1594	1596	1564	1595	1596	1584	1587	1590	1874	1973	1993	< 0.01	< 0.01	< 0.01
RiotOS TWR	4261	1219	1222	1224	593	593	1224	1208	1218	1291	1415	1436	1618	< 0.01	< 0.01	< 0.01

Table 4: Other-Binaries. Minimum (min), median (med), maximum (max) block coverage achieved with each fuzzing framework over five 24 hour trials. P-values indicating statistical significance are calculated using Mann Whitney U tests, at a 0.01 significance level. No binaries showed a statistically significant difference. The highest *min*, *med* and *max* values for each firmware are shown in **bold**.

	Fu	JZZWA	RE	Splits				
Firmware	Blocks in Firmware	Min	\mathbf{Med}	Max	Min	\mathbf{Med}	Max	p-value
6LoWPAN Receiver	6977	2732	3149	3206	2830	3056	3119	0.175
6LoWPAN Sender	6980	2772	2972	3161	2786	3113	3273	0.347
CNC	3614	2561	2718	2733	2209	2510	2611	0.016
Drone	2728	1826	1828	1843	713	1734	1837	0.076
Gateway	4921	2908	2939	3127	2408	2686	2939	0.036
Heat Press	1837	550	554	564	549	550	556	0.164
PLC	2303	637	644	907	629	642	650	0.344
Reflow Oven	2947	1192	1192	1192	1192	1192	1192	N/A
Robot	3034	1305	1313	1315	1298	1306	1319	0.249
Soldering Iron	3656	2302	2353	2457	2229	2457	2465	0.528
Thermostat	4673	3245	3410	3497	3308	3430	3504	0.251
XML Parser	9376	3239	3634	3826	3418	3850	4004	0.175